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OFFICE OF NUCLEAR REACTOR REGULATION

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U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

OFFICE OF NUCLEAR REACTOR REGULATION

3.7.2 SEISMIC SYSTEM ANALYSIS

REVIEW RESPONSIBILITIES

Primary - Structural and Geosciences Branch (ESGB)

Secondary - None

I. AREAS OF REVIEW

The following areas related to the seismic system analysis described in the applicant's safety analysis report (SAR) are reviewed.

1. Seismic Analysis Methods

For all Category I structures, systems, and components, the applicable seismic analysis methods (response spectra, single time history or multiple time histories, equivalent static load) are reviewed. The manner in which the dynamic system analysis method is performed, including the modeling of foundation torsion, rocking, and translation, is reviewed. The method chosen for selection of significant modes and an adequate number of masses or degrees of freedom is reviewed. The manner in which consideration is given in the seismic dynamic analysis to maximum relative displacements between supports is reviewed. In addition, other significant effects that are accounted for in the dynamic seismic analysis such as hydrodynamic effects and nonlinear response are reviewed. If tests or empirical methods are used in lieu of analysis for any Category I structure, the testing procedure, load levels, and acceptance basis are also reviewed. The SRP criteria generally deal with linear elastic analysis coupled with allowable stresses near elastic limits of the structures. However, for certain special cases (e.g., evaluation of as-built structures), the staff has accepted the concept of limited inelastic/nonlinear behavior when appropriate. The actual analysis, incorporating inelastic/nonlinear considerations, is reviewed on a case-by-case basis.

2. Natural Frequencies and Responses

For the operating license review, significant natural frequencies and responses for major Category I structures are reviewed. In addition, the response spectra at major Category I equipment elevations and points of support are reviewed.

3. Procedures Used for Analytical Modeling

The criteria and procedures used in modeling for the seismic system analyses are reviewed. The criteria and bases for determining whether a component or structure is analyzed as part of a system analysis or independently as a subsystem are also reviewed.

4. Soil-Structure Interaction

The design earthquake motion is defined in the "free field," i.e., without the presence of structures, at the ground surface, at a real or hypothetical rock outcrop, or at a rock interface appropriate to the particular site. Because of the deformability of the supporting rock or soil, the resulting motions of the base slab will differ from the corresponding free-field motions. This difference between the base slab motion and the free-field motion is known as the soil-structure interaction (SSI) effect.

As applicable, the definition and location of the control motion and the modeling methods of SSI analysis used in the seismic system analysis and their bases are reviewed. The factors to be considered in accepting a particular modeling method include: (1) the extent of embedment, (2) the depth of soil, and (3) the layering of the soil strata. All SSI analyses must recognize the uncertainties prevalent throughout the phenomenon, including:

a. Transmission of the input motion to the site.

b. The random nature of the soil and rock configuration and material characteristics.

c. Uncertainty in soil constitutive modeling.

d. Nonlinear soil behavior.

e. Coupling between the structures and soil.

f. Lack of symmetry in the soil deposits, which is usually assumed to be symmetrical.

g. The effect of pore water on structural responses, including the effects of variability of ground-water level with time.

h. Effects of partial separation or loss of contact between the structure and the soil during the earthquake.

The procedures by which strain-dependent soil properties (damping, shear modulus, pore pressure), layering, and variation of soil properties are incorporated in the analysis are reviewed.

If applicable, the criteria for determining the location of the bottom boundary and side boundary of the analysis model are reviewed. The procedures used to account for effects of adjacent structures, if any, on structural response in the SSI analysis are reviewed.

To perform a dynamic analysis for an SSI system, it may be necessary to have a well-defined excitation or forcing functions applied at the model boundaries to simulate the earthquake motion. It is therefore required in such cases to generate an excitation system acting at the boundaries such that the response motion of the soil media at the plant site in the free field is identical to the design ground motion. The procedures and theories for regeneration of such an excitation system are reviewed.

Any other modeling methods used for SSI analysis are also reviewed as is any basis for not using an SSI analysis.

5. Development of Floor Response Spectra

The procedures for developing floor response spectra are reviewed. There are several methods for generating in-structure response spectra. One method makes use of time history analysis by considering single or multiple (real or artificial) ground time histories which have spectra that, essentially, envelop the design response spectra. Another method involves a group of analysis techniques generally referred to as the direct solution methods for the generation of in-structure response spectra. These techniques do not involve time history analysis. The basis and justification for the use of either of the above methods are reviewed.

6. Three Components of Earthquake Motion

The procedures by which the three components of earthquake motion are considered in determining the seismic response of structures, systems, and components are reviewed.

7. Combination of Modal Responses

When a response spectrum method is used for calculating the seismic response of structures, systems, or components, the phase relationship between various modes is lost. Only the maximum response for each mode can be determined. The maximum responses for modes do not in general occur at the same time, and these responses have to be combined according to some procedure selected to approximate or bound the response of the system. When a response spectrum method is used, the description of the procedure for combining modal responses (shears, moments, stresses, deflections, and accelerations) is reviewed, including that for modes with closely spaced frequencies.

8. Interaction of Non-Category I Structures with Category I Structures

The design criteria to account for the seismic motion of non-Category I structures or portions thereof in the seismic design of Category I structures or portions thereof are reviewed. The procedures that are used to protect Category I structures from the structural failure of non-Category I structures, due to seismic effects, are reviewed.

9. Effects of Parameter Variations on Floor Responses

The procedures that are used to consider the effects of the expected variations of structural properties, dampings, soil properties, and soil-structure interaction on the floor response spectra and time histories are reviewed.

10. Use of Equivalent Vertical Static Factors

Where applicable, justification for the use of equivalent static factors as vertical response loads for designing Category I structures, systems, and components in lieu of the use of a vertical seismic system dynamic analysis is reviewed.

11. Methods Used to Account for Torsional Effects

The method employed to consider torsional effects in the seismic analysis of Category I structures is reviewed. The review includes evaluation of the conservatism of any approximate methods to account for torsional accelerations in the seismic design of Category I structures.

12. Comparison of Responses

For the operating license review, where applicable, the comparison of seismic responses for major Category I structures using modal response spectrum and time history approaches is evaluated.

13. Analysis Procedure for Damping

The analysis procedure to account for the damping in different elements of the model of a coupled system is reviewed.

14. Determination of Category I Structure Overturning Moments

The description of the method and procedure used to determine design overturning moments for Category I structures is reviewed.

15. Interface Review

Review of geological and seismological information to establish the free-field ground motion is performed as described in SRP Sections 2.5.1 through 2.5.3. The geotechnical parameters and methods employed in the analysis of free-field soil media and soil properties are reviewed as described in SRP Section 2.5.4. The results of the reviews for the operating basis earthquake (OBE) and the safe shutdown earthquake (SSE), soil properties, etc., are used as an integral part of the seismic analysis review of Category I structures.

For those areas of review identified above as being part of other SRP sections, the acceptance criteria necessary for the review and their methods of application are contained in the referenced SRP sections.

II. ACCEPTANCE CRITERIA

The acceptance criteria for the areas of review described in subsection I of this SRP section are given below. Other approaches that can be justified to be equivalent to or more conservative than the stated acceptance criteria may be used. The staff accepts the design of structures, systems, and components that are important to safety and must withstand the effects of earthquakes if the relevant requirements of General Design Criterion (GDC) 2 contained in Appendix A to 10 CFR Part 50 (Ref. 1) and Appendix A to 10 CFR Part 100 (Ref. 2) concerning natural phenomena are complied with. The relevant requirements of GDC 2 and Appendix A to 10 CFR Part 100 are:

1. General Design Criterion 2 - The design basis shall reflect appropriate consideration of the most severe earthquakes that have been historically reported for the site and surrounding area with sufficient margin for the limited accuracy, quantity, and period of time in which historical data have been accumulated.

2. Appendix A to 10 CFR Part 100 - Two earthquake levels, the safe shutdown earthquake (SSE) and the operating basis earthquake (OBE), shall be considered in the design of safety-related structures, components, and systems. Appendix A to 10 CFR Part 100 further states that the design used to ensure that the required safety functions are maintained during and after the vibratory ground motion associated with the safe shutdown earthquake shall involve the use of either a suitable dynamic analysis or a suitable qualification test to demonstrate that structures, systems, and components can withstand the seismic and other concurrent loads, except where it can be demonstrated that the use of an equivalent static load method provides adequate conservatism.

Specific criteria necessary to meet the relevant requirements of GDC 2 and Appendix A to Part 100 are as follows:

1. Seismic Analysis Methods

   The seismic analysis of all Category I structures, systems, and components should use either a suitable dynamic analysis method or an equivalent static load method, if justified. The SRP criteria generally deal with linear elastic analysis coupled with allowable stresses near elastic limits of the structures. However, for certain special cases (e.g., evaluation of as-built structures), the staff has accepted the concept of limited inelastic/nonlinear behavior when appropriate. The actual analysis, incorporating inelastic/nonlinear considerations, is reviewed on a case-by-case basis.

a. <u>Dynamic Analysis Method</u>

A dynamic analysis (e.g., response spectrum method, time history method) should be used. The use of the equivalent static load method is also acceptable if the method can be justified. To be acceptable, dynamic analyses should consider the following items:

(i) Use of appropriate methods of analysis (e.g., time history, response spectrum, frequency domain) acccounting for effects of soil-structure interaction.

(ii) Consideration of the torsional, rocking, and translational responses of the structures and their foundations.

(iii) Use of an adequate number of masses or degrees of freedom in dynamic modeling to determine the response of all Category I and applicable non-Category I structures and plant equipment. (Caution should be exercised in reducing large static models to fewer degrees of freedom models (Ref. 3) for dynamic analysis.) The number is considered adequate when additional degrees of freedom do not result in more than a 10 percent increase in responses. Alternatively, the number of degrees of freedom may be taken equal to twice the number of modes. The adequacy of the number of modes is discussed below.

(iv) Investigation of a sufficient number of modes to ensure participation of all significant modes. The criterion for sufficiency is that the inclusion of additional modes does not result in more than a 10 percent increase in responses. Responses associated with high-frequency modes may be important in some cases (where significant modes have frequencies greater than the frequency at which spectral accelerations return to the zero period acceleration; for example, 33 cycles per second in the case of structures, equipment, and components excited directly by Regulatory Guide 1.60 design spectra). Therefore, a demonstration that adequate consideration is given to the high-frequency modes is required. (See Appendix A for acceptable methods to account for high-frequency modes.)

(v) Consideration of maximum relative displacements among supports of Category I structures, systems, and components.

(vi) Inclusion of significant effects such as piping interactions, externally applied structural restraints, hydrodynamic (both mass and stiffness effects) loads, and nonlinear responses.

b. <u>Equivalent Static Load Method</u>

An equivalent static load method is acceptable if:

(i) Justification is provided that the system can be realistically represented by a simple model and the method produces conservative results in terms of responses. Typical examples or published results for similar structures may be submitted in support of the use of the simplified method.

(ii) The design and associated simplified analysis account for the relative motion between all points of support.

(iii) To obtain an equivalent static load of a structure, equipment, or component that can be represented by a simple model, a factor of 1.5 is applied to the peak acceleration of the applicable floor response spectrum. A factor of less than 1.5 may be used if adequate justification is provided.

2. Natural Frequencies and Response Loads

To be acceptable for the operating license review, the following information should be provided:

a. A summary of natural frequencies, mode shapes, modal and total responses for a representative number of major Category I structures, including the containment building, or a summary of the total responses if the method of direct integration is used.

b. A time history of acceleration (or other parameters of motion) or response spectrum used in design at the major plant equipment elevations and points of support.

c. For multiple time history option, procedures used to account for uncertainties (by variation of parameters) and to develop design responses, including justification for the statistical relationship between input design response spectra and output responses. (For example, if the average response spectra generated from the multiple design time histories are used to envelop the design response spectra, then the average responses generated from the multiple analyses are used in design.)

3. Procedures Used for Analytical Modeling

A nuclear power plant facility consists of very complex structural systems. To be acceptable, the stiffness, mass, and damping characteristics of the structural systems should be adequately incorporated into the analytical models. Specifically, the following items should be considered in analytical modeling:

a. Designation of Systems Versus Subsystems

Major Category I structures that are considered in conjunction with the foundation and its supporting media are defined as "seismic systems." Other Category I structures, systems, and components that are not designated as "seismic systems" should be considered as "seismic subsystems."

b. Decoupling Criteria for Subsystems

It can be shown, in general, that frequencies of systems and subsystems have a negligible effect on the error due to decoupling. It can be shown that the mass ratio, R_m, and the frequency ratio, R_f, govern the results where R_m and R_f are defined as:

$$R_m = \frac{\text{Total mass of the supported subsystem}}{\text{Total mass of the supporting system}}$$

$$R_f = \frac{\text{Fundamental frequency of the supported subsystem}}{\text{Dominant frequency of the support motion}}$$

The following criteria are acceptable:

(i) If $R_m < 0.01$, decoupling can be done for any R_f.

(ii) If $0.01 \leq R_m \leq 0.1$, decoupling can be done if $0.8 \geq R_f \geq 1.25$.

(iii) If $R_m > 0.1$, a subsystem model should be included in the primary system model.

If the subsystem is rigid compared to the supporting system, and also is rigidly connected to the supporting system, it is sufficient to include only the mass of the subsystem at the support point in the primary system model. On the other hand, in case of a subsystem supported by very flexible connections, e.g., pipe supported by hangers, the subsystem need not be included in the primary model. In most cases, the equipment and components, which come under the definition of subsystems, are analyzed (or tested) as a decoupled system from the primary structure and the seismic input for the former is obtained by the analysis of the latter. One important exception to this procedure is the reactor coolant system, which is considered a subsystem but is usually analyzed using a coupled model of the reactor coolant system and primary structure.

c. Lumped Mass Considerations

The acceptance criteria given under subsection II.1.a(iii) of this SRP section are applicable.

d. Modeling for Three-Component Input Motion

In general, three-dimensional models should be used for seismic analyses. However, simpler models can be used if justification can be provided that the coupling effects of those degrees of freedom that are omitted from the three-dimensional models are not significant.

4. Soil-Structure Interaction

A complete soil-structure interaction (SSI) analysis must properly account for all effects due to kinematic and inertial interaction for surface or embedded structures. Any analysis method based on either a direct approach or a substructure approach can be used provided the following conditions are met:

a. The structure, foundation, and soil are properly modeled to ensure that the results of analyses are within the range of applicability of the particular method employed.

b. The input motion at the base of a discrete soil model or soil column should produce the specified design spectra at the free surface of the soil profile in the free field (finished grade).

It is noted that there is enough confidence in the current methods used to perform the SSI analysis to capture the basic phenomenon and provide adequate design information; however, the confidence in the ability to implement these methodologies is uncertain. Therefore, in order to ensure proper implementation, the following considerations should be addressed in performing SSI analysis (Ref. 4):

a. Perform sensitivity studies to identify important parameters (e.g., bonding and debonding of side walls, nonsymmetry of embedment, location of boundaries) and to assist in judging the adequacy of the final results. These sensitivity studies can be performed by the use of well-founded and properly substantiated simple models to give better insight;

b. Through the use of some appropriate benchmark problems, the user should demonstrate its capability to properly implement any SSI methodologies; and

c. Perform enough parametric studies with the proper variation of parameters (e.g., soil properties) to address the uncertainties (as applicable to the given site) discussed in subsection I.4 of this SRP section.

For sites where SSI effects are considered insignificant and fixed base analyses of structures are performed, bases and justification for not performing SSI analyses are reviewed on a case-by-case basis. If the SSI analysis is not required, the input motion at the base of the structures will be the design motion reviewed in SRP Section 3.7.1.

The acceptance criteria for the constituent parts of the entire SSI system are summarized as follows:

a. Modeling of Structure

The acceptance criteria given under subsection II.3 of this SRP section are applicable.

b. Modeling of Supporting Soil

The effect of embedment of structure, ground-water effects, and the layering effect of soil should be accounted for. For the half-space modeling of the soil media, the lumped parameter (soil spring) method and the compliance function methods are acceptable. For the method of modeling soil media with finite boundaries, all boundaries should be properly simulated and the use of types of boundaries should be justified and reviewed on a case-by-case basis. Finite element and finite difference methods are acceptable methods for discretization of a continuum. The properties used in the SSI analysis should be those corresponding to the low strains that are consistent with the realistic soil strain developed during the design earthquake. Use of high strain soil parameters needs to be adequately justified on a case-by-case basis.

For structures supported on rock or rock-like material, a fixed base assumption is acceptable. Such materials are defined by a shear wave velocity of 3500 feet per second or greater at a shear strain of 10^{-3} percent or smaller when considering preloaded soil conditions due to the structure (Ref. 5). A comparison of fundamental natural frequencies of the fixed base and interacting structures can be used to justify the fixed base assumption (Ref. 6).

c. Generation of Excitation System

The control motion should be consistent with the properties of the soil profile. For profiles consisting of competent soil or rock, with relatively uniform variation of properties with depth, the control motion should be located at the soil surface at the top of the finished grade. For profiles consisting of one or more thin soil layers overlaying competent material, the control motion should be located at an outcrop (real or hypothetical) at the top of the competent material in the vicinity of the site. Variation of amplitude and frequency content with depth may be considered for partially embedded structures. The spectral amplitude of the acceleration response spectra (horizontal component of motion) in the free field at the foundation depth shall be not less than 60 percent of the corresponding design response spectra at the finished grade in the free field (Ref. 5). When variation in soil properties are considered (as required by the Specific Guidelines for SSI Analysis below), the 60 percent limitation may be satisfied using an envelope of the three spectra corresponding to the three soil properties.

If the accompanying rotational components of motion are ignored, no reduction is permitted in the horizontal component at the foundation level.

Specific Guidelines for SSI Analysis

The following specific guidelines are provided here to facilitate the review and draw the attention of reviewers to some important aspects of the SSI analysis. These guidelines are not necessarily requirements for the acceptance of any methodologies or an SSI analysis.

o The behavior of soil, though recognized to be nonlinear, can often be approximated by linear techniques. Truly nonlinear analysis is not required unless the comparison of results from large-scale tests or actual earthquakes and analytical results indicate deficiencies that cannot be accounted for in any other manner. The nonlinear soil behavior may be accounted for by the following:

- Using equivalent linear soil material properties typically determined from an iterative linear analysis of the free-field soil deposit. This accounts for the primary nonlinearity, or

- Performing an iterative linear analysis of the coupled soil-structure system. This accounts for the primary and secondary nonlinearities.

  In the event the nonlinear analysis is chosen, the results of the nonlinear analysis should be judged on the basis of the linear or equivalent linear analysis (Ref. 4).

o Superposition of horizontal and vertical response as determined from separate analyses is acceptable (assuming nonlinear effects are not important) considering the simple material models now available.

o The strain-dependent soil properties (e.g., shear modulus, damping) estimated from analysis of the seismic motion in the free field shall be consistent with the geotechnical information reviewed in SRP Section 2.5.4. Reports on recent earthquakes (e.g., Coalinga) seem to show that there may not be a decrease in shear modulus or increase in damping under high strains.

o Unless the site is well investigated, the variation in soil properties should be considered by performing SSI analyses using three sets of values (defined in terms of shear moduli and soil hysteretic damping ratio). These three analyses should be performed using the average (or best estimate) value, twice the average value and half the average value of the low strain shear modulus (G_{max} defined at 10^{-4} percent peak shear strain). The same shear modulus degradation (G/G_{max}) and hysteretic damping (D) curves as function of peak shear strain can be used for each of these three analyses. Final values of shear modulus and damping ratio used for each of the analyses are to be compatible with the strain levels expected in the free field consistent with earthquake levels. In no case should the lower bound shear modulus be less than that value consistent with standard foundation analysis that yields foundation settlement under static loads exceeding design allowables. The upper bound shear modulus should not be less than the best estimate shear modulus defined at low strain and as determined from the geophysical testing program. In no case should the material soil damping as expressed by the hysteretic damping ratio D (defined in Ref. 5) exceed 15 percent.

o For dipping soil and rock strata, it is necessary to account for the coupling between the horizontal and vertical degrees of freedom in the stiffness and free-field seismic motion definitions. For such sites, modeling and analysis techniques are reviewed on a case-by-case basis.

o *Finite Boundary Modeling or Direct Solution Technique*

  The direct solution method is characterized as follows:

  - Each analysis of the soil and structures is performed in one step.

- Finite element or finite difference discrete methods of analysis are used to spatially discretize the soil-structure system.

- Definition of the motion along the boundaries of the model (bottom and sides) is either known, assumed, or computed as a precondition of the analysis.

For the direct solution technique, spatial representation typically involves two-dimensional, plane strain mathematical models or axisymmetric models. Dynamic analysis can be performed using either frequency-domain (limited to linear analysis) or time-integration methods. The mesh size should be adequate for representing the static stress distribution under the foundation and transmitting the frequency content of interest. The two-dimensional approximation of three-dimensional problems may have to be justified in some special situations.

Two mathematical representations of the model side boundaries are available for use in the direct solution approach--simple or viscous boundaries and transmitting boundaries. The location of the simple or viscous boundaries is dependent on strain and damping in the soil and is typically thrice the base dimension from the structure. The side boundary nodes can be either "constrained," in which case free-field displacements are specified, or "free," in which case forces are specified. When using the transmitting boundaries, it is possible to place the boundaries immediately adjacent to the structure if secondary nonlinearities in the soil are ignored.

The following limitations should be observed for deep soil sites:

- The model depth, generally, should be at least twice the base dimension below the foundation level, which should be verified by parametric studies.

- The fundamental frequency of the soil (or backfill) stratum should be well below the structural frequencies of interest.

- All structural modes of significance should be included.

o Half Space or Substructure Solution Technique

The substructure (3-step) approach comprises the following steps:

(1) Determine the motion of the massless foundation, including both translational and rotational components.

(2) Determine the foundation stiffness in terms of frequency-dependent impedance functions.

(3) Perform soil-structure interaction analysis.

Step (1) requires that assumptions be made about the mechanism of wave motion at the site. The foundation motion may be determined by a number of techniques, including:

- Analytic functions

- Boundary integral equations

- Finite element and difference methods.

In calculating the foundation motion by one of these methods, the foundation mat is usually assumed to be rigid and bonded to the soil. However, this is not a necessary assumption because additional degrees of freedom may be specified for the foundation. Again, it must be emphasized that, in general, a translation specified on the surface of the soil produces a translation and rotation of the massless foundation.

Stiffness characteristics of the soil, required in Step (2), may also be determined by analytic functions, boundary integral equations, and finite element and difference methods. When calculating the soil stiffness, variations in soil characteristics with excitation level should be accounted for.

Typically, the SSI analysis of Step (3) is done using frequency-domain methods. That the frequency dependence of soil impedances be accounted for is believed to be important.

For the case where time history analyses are performed using frequency-independent soil spring parameters, the specific values of damping coefficients tend to be unrealistically large. Therefore, the spring and damping coefficients will be reviewed on a case-by-case basis.

5. Development of Floor Response Spectra

To be acceptable, the floor response spectra should be developed taking into consideration the three components of the earthquake motion. The individual floor response spectral values for each frequency are obtained for one vertical and two mutually perpendicular horizontal earthquake motions and are combined according to the "square root of the sum of the squares" (SRSS) method to predict the total floor response spectrum for that particular frequency (Ref. 7). If the three components of the motion are applied simultaneously (also see subsection II.6), the SRSS approach is not required.

When a single artificial time history is used to generate the floor response spectra, all the provisions of Reference 7, including peak broadening requirements, shall apply. The use of single artificial time history should also be justified as outlined in subsection II.1.b of SRP Section 3.7.1.

The use of multiple time histories to generate floor response spectra is reviewed and accepted on a case-by-case basis. Particularly, the basis for procedures used to account for uncertainties (by variation of parameters) are evaluated. The same acceptance criteria are used for floor response spectra as are used for design response spectra in subsection II.1.b of SRP Section 3.7.1. For example, if the average response spectra generated from the multiple design time histories are used to envelop the design response spectra, then the average floor response spectra generated from the multiple analyses (each of which used one of the multiple design time histories) are used in design. Justification should be provided for the statistical relationship between input ground response spectra and output floor response spectra.

The methods used for direct generation of floor spectra are reviewed and accepted on a case-by-case basis.

6. Three Components of Earthquake Motion

Depending upon what basic methods are used in the seismic analysis, i.e., response spectra or time history method, the following two approaches are considered acceptable for the combination of three-dimensional earthquake effects (Ref. 8).

a. Response Spectra Method

When the response spectra method is adopted for seismic analysis, the maximum structural responses due to each of the three components of earthquake motion should be combined by taking the square root of the sum of the squares of the maximum codirectional responses caused by each of the three components of earthquake motion at a particular point of the structure or of the mathematical model.

b. Time History Analysis Method

When the time history analysis method is employed for seismic analysis, two types of analysis are generally performed depending on the complexity of the problem: (1) To obtain maximum responses due to each of the three components of the earthquake motion, the method for combining the three-dimensional effects is identical to that described in item 6.a except that the maximum responses are calculated using the time history method instead of the response spectrum method. (2) To obtain time history responses from each of the three components of the earthquake motion and combine them at each time step algebraically, the maximum response can be obtained from the combined time solution. When this method is used, the components of earthquake motions specified in the three different directions should be statistically independent.

7. Combination of Modal Responses

When the response spectrum method of analysis is used to determine the dynamic response of damped linear systems, in general, the most probable response is obtained as the square root of the sum of the squares of the responses from individual modes. Thus, the most probable system response, R, is given by:

$$R = \left(\sum_{k=1}^{N} R_k^2\right)^{1/2} \tag{1}$$

where R_k is the response for the k^{th} mode and N is the number of significant modes considered in the modal response combination.

When modes with closely spaced modal frequencies exist (two modes having frequencies within 10 percent of each other), the methods delineated in Reference 8 are acceptable. Use of other methods for considering closely spaced modes, such as those outlined in References 4 and 9 will be reviewed and accepted on a case-by-case basis. Acceptance criteria for the adequate consideration of high-frequency modes are provided in Appendix A to this SRP section.

8. Interaction of Non-Category I Structures with Category I Structures

To be acceptable, the interfaces between Category I and non-Category I structures and plant equipment must be designed for the dynamic loads and displacements produced by both the Category I and non-Category I structures and plant equipment. In addition, a statement indicating the fact that all non-Category I structures meet any one of the following requirements should be provided.

a. The collapse of any non-Category I structure will not cause the non-Category I structure to strike a seismic Category I structure or component.

b. The collapse of any non-Category I structure will not impair the integrity of seismic Category I structures or components.

c. The non-Category I structures will be analyzed and designed to prevent their failure under SSE conditions in a manner such that the margin of safety of these structures is equivalent to that of Category I structures.

9. Effects of Parameter Variations on Floor Response Spectra

Consideration should be given in the analysis to the effects on floor response spectra (e.g., peak width and period coordinates) of expected variations of structural properties, dampings, soil properties, and soil-structure interactions. The acceptance criteria for the consideration of the effects of parameter variations are provided in subsection II.5 of this SRP section.

10. Use of Equivalent Vertical Static Factors

The use of equivalent static load factors as vertical response loads for the seismic design of all Category I structures, systems, and components in lieu of the use of a vertical seismic system dynamic analysis is acceptable only if it can be justified that the structure is rigid in the vertical direction. The criterion for rigidity is that the lowest frequency in the vertical direction is more than 33 cps.

11. Methods Used to Account for Torsional Effects

An acceptable method of treating the torsional effects in the seismic analysis of Category I structures is to carry out a dynamic analysis that incorporates the torsional degrees of freedom. An acceptable alternative, if properly justified, is the use of static factors to account for torsional accelerations in the seismic design of Category I structures in lieu of the use of a combined vertical, horizontal, and torsional system dynamic analysis. To account for accidental torsion, an additional eccentricity of ± 5 percent of the maximum building dimension at the level under consideration shall be assumed for both directions.

12. Comparison of Responses

The responses obtained from both response spectrum and time history modal analyses at selected points in typical Category I structures should be compared to demonstrate approximate equivalency between the two methods.

13. Analysis Procedure for Damping

Either the composite modal damping approach or the modal synthesis technique can be used to account for element-associated damping.

Use of composite modal damping for computing the response of systems with nonclassical modes may lead to unconservative results (Ref. 10). Therefore, the composite modal damping approach is acceptable provided the composite modal damping is limited to 20 percent. One of the other methods mentioned below is generally applicable if the composite modal damping exceeds 20 percent.

a. Time domain analysis using complex modes/frequencies,

b. Frequency domain analysis, or

c. Direct integration of uncoupled equation of motion.

For the composite modal damping approach, two techniques of determining an equivalent modal damping matrix or composite damping matrix are commonly used. They are based on the use of the mass or stiffness as a weighting function in generating the composite modal damping. The formulations lead to:

$$\bar{\beta}_j = \{\phi\}^T [\bar{M}] \{\phi\} \tag{2}$$

$$\beta_j = \frac{\{\phi\}^T [\bar{K}] \{\phi\}}{K^*} \tag{3}$$

where

$K^* = \{\phi\}^T [K] \{\phi\}$,

$[K]$ = assembled stiffness matrix,

$\bar{\beta}_j$ = equivalent modal damping ratio of the j^{th} mode,

$[\bar{K}]$, $[\bar{M}]$ = the modified stiffness or mass matrix constructed from element matrices formed by the product of the damping ratio for the element and its stiffness or mass matrix, and

$\{\phi\}$ = j^{th} normalized modal vector.

For models that take the soil-structure interaction into account by the lumped soil spring approach, the method defined by equation (3) is acceptable. For fixed base models, either equation (2) or (3) may be used. Other techniques based on modal synthesis have been developed and are particularly useful when more detailed data on the damping characteristics of structural subsystems are available. The modal synthesis analysis procedure consists of (1) extraction of sufficient modes from the structure model, (2) extraction of sufficient modes from the finite element soil model, and (3) performance of a coupled analysis using the modal synthesis technique, which uses the data obtained in steps (1) and (2) with appropriate damping ratios for structure and soil subsystems. This method is based upon satisfaction of displacement compatibility and force equilibrium at the system interfaces and uses subsystem eigenvectors as internal generalized coordinates. This method results in a nonproportional damping matrix for the composite structure, and equations of motion have to be solved by direct integration or by uncoupling them by use of complex eigenvectors.

Other techniques for estimating the equivalent modal damping of a soil-structure interaction model are reviewed on a case-by-case basis.

14. Determination of Category I Structure Overturning Moments

To be acceptable, the determination of the design overturning moment should incorporate the following items:

a. Three components of input motion.

b. Conservative consideration of vertical and lateral seismic forces.

III. REVIEW PROCEDURES

For each area of review, the following procedure is implemented. The reviewer will select and emphasize material from the procedures given below, as may be appropriate for a particular case. The scope and depth of review procedures must be such that the acceptance criteria described above are met.

1. Seismic Analysis Methods

For all Category I structures, systems, and components, the applicable methods of seismic analysis (response spectra, time history, equivalent static load) are reviewed to confirm that the techniques employed are in accordance with the acceptance criteria as given in subsection II.1 of this SRP section. If empirical methods or tests are used in lieu of analysis for any Category I structure, these are evaluated to determine whether or not the assumptions are conservative, and whether the test procedure adequately models the seismic response.

2. Natural Frequencies and Response Loads

For the operating license review, the summary of natural frequencies and response loads is reviewed for compliance with the acceptance criteria in subsection II.2 of this SRP section.

3. Procedures Used for Analytical Modeling

The procedures used for modeling of seismic system analyses are reviewed to determine whether the three-dimensional characteristics of structures are properly modeled in accordance with the acceptance criteria of subsection II.3 of this SRP section and whether all significant degrees of freedom have been incorporated in the models. The criteria for decoupling of a structure, equipment, or component and analyzing it separately as a subsystem are reviewed for conformance with the acceptance criteria given in subsection II.3 of this SRP section.

4. Soil-Structure Interaction

The methods of soil-structure interaction analysis used are examined to determine that the techniques employed are in accordance with the acceptance criteria as given in subsection II.4 of this SRP section. Typical mathematical models for soil-structure interaction analysis are reviewed to ensure the adequacy of the representation in accordance with subsection II.4 of this SRP section. In addition, the methods used to assess the effects of adjacent structures on structural response in soil-structure interaction analysis are reviewed to establish their acceptability.

5. Development of Floor Response Spectra

Procedures for developing the floor response spectra are reviewed to verify that they are in accordance with the acceptance criteria specified in subsection II.5 of this SRP section. If a modal response spectrum method of analysis is used to develop the floor response spectra, its conservatism compared to that of a time history approach is reviewed.

6. Three Components of Earthquake Motion

The procedures by which the three components of earthquake motion are considered in determining the seismic response of structures, systems, and components are reviewed to determine compliance with the acceptance criteria of subsection II.6 of this SRP section.

7. Combination of Modal Responses

The procedures for combining modal responses (shears, moments, stresses, deflections, and accelerations) are reviewed to determine compliance with the acceptance criteria of subsection II.7 of this SRP section when a response spectrum modal analysis method is used.

8. Interaction of Non-Category I Structures with Category I Structures

The design and analysis criteria for interaction of non-Category I structures with Category I structures are reviewed to ensure compliance with the acceptance criteria of subsection II.8 of this SRP section.

9. Effects of Parameter Variations on Floor Response Spectra

The seismic system analysis is reviewed to determine whether the analysis considered the effects of expected variations of structural properties, dampings, soil properties, and soil-structure interactions on floor response spectra (e.g., peak width and period coordinates) and to determine compliance with the acceptance criteria of subsection II.9 of this SRP section.

10. Use of Equivalent Vertical Static Factors

Use of constant static factors as response loads in the vertical direction for the seismic design of any Category I structure, system, or component in lieu of a detailed dynamic method is reviewed to determine that constant vertical static factors are used only if the structure is rigid in the vertical direction.

11. Methods Used to Account for Torsional Effects

The methods of seismic analysis are reviewed to determine that the torsional effects of vibration are incorporated by including the torsional degrees of freedom in the dynamic model. Justification provided by the applicant for the use of any approximate method to account for torsional effects is judged to ensure that it results in a conservative design.

12. Comparison of Responses

Where applicable, the responses obtained from both time history and response spectrum methods at selected points in major Category I structures are compared to judge the accuracy of the analyses conducted. The applicant is asked to discuss the reasons for the large differences in the results of the two methods.

13. Analysis Procedure for Damping

The analysis procedure to account for damping in different elements of the model of a coupled system is reviewed to determine that it is in accordance with the acceptance criteria of subsection II.13 of this SRP section.

14. Determination of Category I Structure Overturning Moments

Methods to determine Category I structure overturning moments are reviewed to determine compliance with the acceptance criteria of subsection II.14 of this SRP section.

Any matters identified during the review of the SAR where additional information or justification are needed are included in the "Additional Technical Information Request." Such requests not only identify any portions of the seismic system analysis considered unacceptable without further justification, but also specify the changes that should be made in the SAR to meet the acceptance criteria. Subsequent amendments of the SAR received in response to these staff requests are reviewed for conformance with the staff positions.

IV. EVALUATION FINDINGS

(Combined for Sections 3.7.2 and 3.7.3)
The reviewer verifies that sufficient information has been provided and that his evaluation is sufficiently complete and adequate to support conclusions of the following type, to be included in the staff's safety evaluation report:

The staff concludes that the plant design is acceptable and meets the requirements of General Design Criterion 2 and Appendix A to 10 CFR Part 100. This conclusion is based on the following: The applicant has met the requirements of GDC 2 and Appendix A to 10 CFR Part 100 with respect to the capability of the structures to withstand the effects of the earthquakes so that their design reflects:

1. Appropriate consideration for the most severe earthquake recorded for the site with an appropriate margin (GDC 2). Consideration of two levels of earthquakes (Appendix A, 10 CFR Part 100),

2. Appropriate combination of the effects of normal and accident conditions with the effect of the natural phenomena, and

3. The importance of the safety functions to be performed (GDC 2). The use of a suitable dynamic analysis or a suitable qualification test to demonstrate that structures, systems, and components can withstand the seismic and other concurrent loads, except where it can be demonstrated that the use of an equivalent static load method provides adequate consideration (Appendix A, 10 CFR Part 100).

The applicant has met the requirements of item 1 listed above by use of the acceptable seismic design parameters as per SRP Section 3.7.1. The combination of earthquake-resulted loads with those resulting from normal and accident conditions in the design of Category I structures as specified in SRP Sections 3.8.1 through 3.8.5 will be in conformance with item 2 listed above.

The scope of review of the seismic system and subsystem analysis for the plant included the seismic analysis methods for all Category I structures, systems, and components. It included review of procedures for modeling, seismic soil-structure interaction, development of floor response spectra, inclusion of torsional effects, seismic analysis of Category I concrete dams, evaluation of Category I structure overturning, and determination of composite damping. The review included design criteria and procedures for evaluation of the interaction of non-Category I structures with Category I structures and the effects of parameter variations on floor response spectra.

The review also included criteria and seismic analysis procedures for Category I buried piping outside containment and above-ground Category I tanks.

The system and subsystem analyses are performed by the applicant on an elastic and linear basis. Time history methods form the bases for the analyses of all major Category I structures, systems, and components. When the modal response spectrum method is used, the methods used in combining modal responses are in conformance with the position of Regulatory Guide 1.92 and also meet high-frequency mode contribution requirements. The square root of the sum of the squares of the maximum codirectional responses is used in accounting for three components of the earthquake motion for both the time history and response spectrum methods. Floor spectra inputs to be used for design and test verifications of structures, systems, and components are generated from the time history method and they are in conformance with the position of Regulatory Guide 1.122. A vertical seismic system dynamic analysis is employed for all structures, systems, and components where analyses show significant structural amplification in the vertical direction. Torsional effects and stability against overturning are considered.

A coupled structure and soil model is used to evaluate soil-structure interaction effects upon seismic responses. Appropriate nonlinear stress-strain and damping relationships for the soil are considered in the analysis. We conclude that the use of the seismic structural analysis procedures and criteria delineated above by the applicant provides an acceptable basis for the seismic design which is in conformance with the requirements of item 3 listed above.

V. IMPLEMENTATION

The following is intended to provide guidance to applicants and licensees regarding the NRC staff's plans for using this SRP section.

Except in those cases in which the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the method described herein will be used by the staff in its evaluation of conformance with Commission regulations.

Implementation schedules for conformance to parts of the method discussed herein are contained in the referenced regulatory guides.

The provisions of this SRP section apply to review of construction permit (CP), preliminary design approval (PDA), final design approval (FDA), and combined license (CP/OL) applications docketed after the date of issuance of this SRP section. Operating license (OL) and final design approval (FDA) applications, whose CP and PDA reviews were conducted prior to the issuance of this revision to SRP Section 3.7.2, will be reviewed in accordance with the acceptance criteria given in the SRP Section 3.7.2, Revision 1, dated July 1981.

VI. REFERENCES

1. 10 CFR Part 50, Appendix A, General Design Criterion 2, "Design Bases for Protection Against Natural Phenomena."

2. 10 CFR Part 100, Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants."

3. C. A. Miller and A. J. Philippacopoulos, "Application of Reduction Methods to Nuclear Power Plant Structures," NUREG/CR-3074, April 1983.

4. "Proceedings of the Workshop on Soil-Structure Interaction," Bethesda, MD, NUREG/CP-0054, June 16-18, 1986.

5. ASCE Standard 4-86, "Seismic Analysis of Safety-Related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety-Related Nuclear Structures," American Society of Civil Engineers, September 1986.

6. A. S. Veletsos, "Dynamics of Structure-Foundation Systems," Structural and Geotechnical Mechanics, W. J. Hall, editor, Prentice-Hall, Inc., Englewood Cliffs, NJ, pp. 333-361, 1977.

7. Regulatory Guide 1.122, "Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components."

8. Regulatory Guide 1.92, "Combining Modal Responses and Special Components in Seismic Response Analysis."

9. D. W. Coats, "Recommended Revisions to Nuclear Regulatory Commission Seismic Design Criteria," NUREG/CR-1161, May 1980.

10. C. A. Miller, C. J. Costantino, and A. J. Philippacopoulos, "High Soil-Structure Damping Combined with Low Structural Damping," 7th Structural Mechanics in Reactor Technology (SMiRT) Paper K 10/10, Chicago, IL, 1985.

APPENDIX A TO SRP SECTION 3.7.2

ACCEPTABLE METHODOLOGIES TO ACCOUNT FOR HIGH-FREQUENCY MODES

Section 3.7.2 of the SRP requires that sufficient modes be included in a dynamic response analysis to ensure that an inclusion of additional modes does not result in more than a 10 percent increase in responses. The implementation of this requirement may require the inclusion of modes with natural frequencies at which the spectral acceleration roughly returns to the zero-period acceleration. The square-root-of-sum-of-squares (SRSS) combination of such modes is highly inaccurate and may be significantly unconservative.

The SRSS combination of modal responses is based on the premise that peak modal responses are randomly phased in time. This assumption has been shown to be adequate throughout the majority of the frequency range for earthquake-type responses. However, this premise is invalid at frequencies approximately equal to or greater than those at which spectral acceleration (S_a) roughly returns to the zero-period acceleration (ZPA). Phasing of the maximum response from modes at such frequencies (roughly 33 Hz and greater for the Regulatory Guide 1.60 response spectra) will be essentially deterministic and the structure simply responds to the inertial forces from the peak ZPA in a pseudostatic fashion.

There are several solutions to the problem of how to combine responses associated with high-frequency modes when the lower-frequency modes do not adequately define the mass content of the structure.

The following is one acceptable procedure for incorporating responses associated with high-frequency modes.

Step 1. Determine the modal responses only for those modes that have natural frequencies less than that at which the spectral acceleration approximately returns to the ZPA (33 Hz for the Regulatory Guide 1.60 response spectra). Combine such modes in accordance with the methods delineated in Reference 8.

Step 2. For each degree of freedom (DOF) included in the dynamic analysis, determine the fraction of DOF mass included in the summation of all of the modes included in Step 1. This fraction d_i for each DOF i is given by:

$$d_i = \sum_{n=1}^{N} c_n \times \phi_{n,i}$$

where

n is order of the mode under consideration,

N is the number of modes included in Step 1,

$\phi_{n,i}$ is the nth natural mode of the system, and

c_n is the participation factor given by:

$$c_n = \frac{\{\phi_n\}^T \{1\}}{\{\phi_n\}^T [m] \{\phi_n\}}$$

Next, determine the fraction of DOF mass not included in the summation of these modes:

$$e_i = d_i - \delta_{ij}$$

where δ_{ij} is the Kronecker delta, which is one if DOF i is in the direction of the earthquake motion and zero if DOF i is a rotation or not in the direction of the earthquake input motion.

If, for any DOF i, the absolute value of this fraction e_i exceeds 0.1, one should include the response from higher modes with those included in Step 1.

Step 3. Higher modes can be assumed to respond in phase with the ZPA and, thus, with each other; hence, these modes are combined algebraically, which is equivalent to pseudostatic response to the inertial forces from these higher modes excited at the ZPA. The pseudostatic inertial forces associated with the summation of all higher modes for each DOF i are given by:

$P_i = ZPA \times M_i \times e_i$ where

P_i is the force or moment to be applied at DOF i.
M_i is the mass or mass moment of inertia associated with DOF i.

The structure is then statically analyzed for this set of pseudostatic inertial forces applied to all of the degrees of freedom to determine the maximum responses associated with high-frequency modes not included in Step 1.

Step 4. The total combined response to high-frequency modes (Step 3) are combined by the square-root-of-sum-of-squares method with the total combined response from lower-frequency modes (Step 1) to determine the overall structural peak responses.

This procedure requires the computation of individual modal responses only for lower-frequency modes (below 33 Hz for the Regulatory Guide 1.60 response spectrum). Thus, the more difficult higher-frequency modes need not be determined. The procedure ensures inclusion of all modes of the structural model and proper representation of DOF masses.

An acceptable alternative to this procedure is as follows:

Modal responses are computed for enough modes to ensure that the inclusion of additional modes does not increase the total response by more than 10 percent. Modes that have natural frequencies less than that at which the spectral acceleration approximately returns to the ZPA (33 Hz in the case of Regulatory

Guide 1.60 response spectra) are combined in accordance with Reference 8. Higher-mode responses are combined algebraically (i.e., retain sign) with each other. The absolute value of the combined higher modes is then added directly to the total response from the combined lower modes.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This revision of SRP Section 3.7.2 has the following major changes:

(1) For soil-structure interaction analysis, the reduction of control motion with depth is now acceptable but limited to 40% from the surface motion. Enveloping requirement of results from two methods is eliminated. Any single approach is acceptable with emphasis on proper implementation.
(2) Guidance for modal combination of high frequency modes are provided and an acceptable approach is outlined in Appendix A.
(3) Option of direct generation of floor response spectra is included.

Additional reference are provided for further guidance.

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